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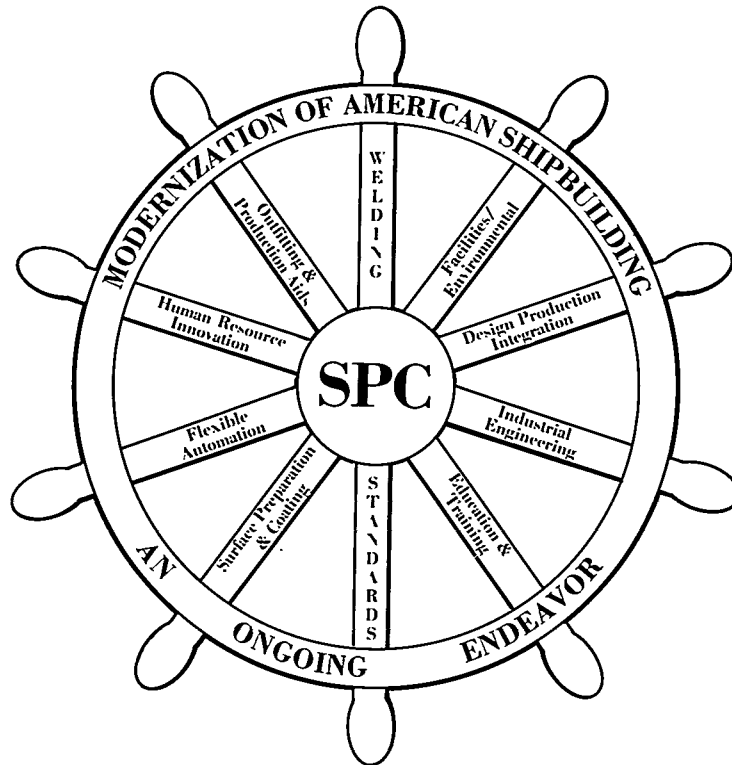
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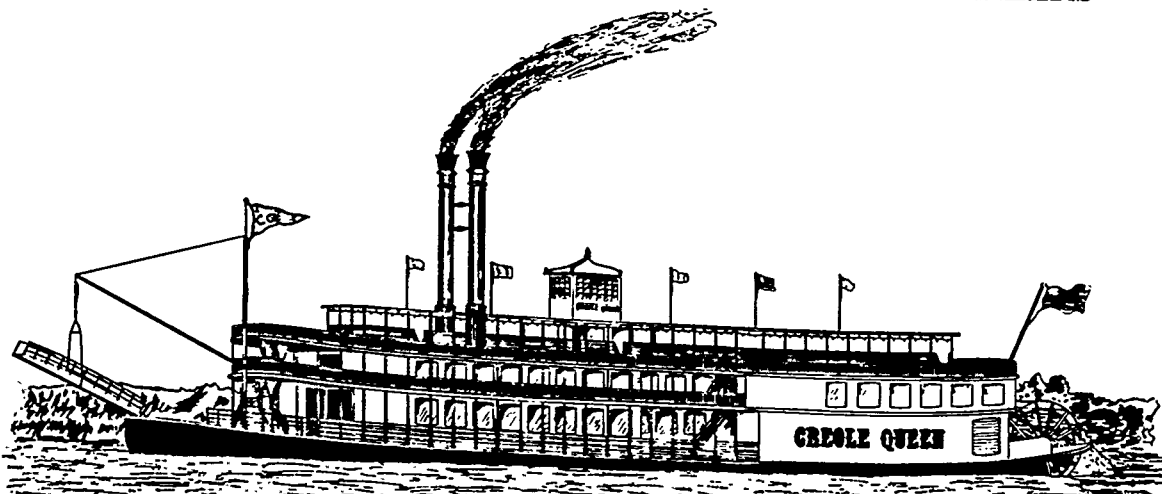
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High Strength Steels Produced by Advanced Metallurgical Processes

No. 21

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BACKGROUND

Increased strength of steels used for ship structural applications have traditionally been achieved with higher alloy content. Depending on the alloying elements chosen, the increased strength is achieved at a cost in weldability and toughness.

Recent developments in the control of properties through precise thermomechanical processing (control of rolling temperature regimes, rolling thickness reductions and cooling rates) and advanced steelmaking techniques, have led to the creation of steel with increased strength and toughness, while maintaining modest carbon equivalents to provide good weldability. There is reason to believe that excellent results will be attainable with the new families of high strength steels which are now or are expected to become commercially available in the near future. A more detailed description of the metallurgical processing is included in Appendix A.

It is expected that the use of the new high strength steels will prove attractive in many marine applications, because of their potential relative insensitivity to heat input, HAZ hardening, and their potential for reduced requirements for preheat.

Data generated in a current SP-7 project studying high heat input effects on 50 ksi yield strength steels produced by thermomechanical processing has indicated superior notch toughness and resistance to heat input [1]. Data in the technical literature has indicated similar promise for higher yield strength steels.

OBJECTIVE

The immediate objective of this investigation was to explore the potential advantages of new high strength (65 to 120 ksi yield) steels produced by advanced steelmaking and on-line processing techniques for marine applications.

A longer term objective is to facilitate the introduction to the shipbuilding industry of the new high strength steels processed by advanced on-line processing techniques with toughness and weldability properties beyond those currently available.

ACHIEVEMENT

The study has provided a preliminary characterization of newly developed steels with yield strengths varying from 65 ksi to 120 ksi. On the basis of the preliminary data obtained, it appears that by use of advanced metallurgical processes, high strength steels can be produced which provide improved toughness and weldability; the alloying elements required for such steels could be substantially lower than that required for conventionally processed quenched and tempered steels of the same strength and toughness levels.

APPROACH

Candidate steels over the strength range of interest which were being made by thermomechanical controlled rolling with on line cooling were obtained. In addition, a fourth steel produced by conventional quench and temper techniques was included. Each steel was subjected to appropriate tests to indicate tensile, Charpy V-Notch, Nil-Ductility Transition (NDT) (drop weight) and dynamic tear properties. Controlled thermal severity (CTS) testing was also conducted to provide preliminary information as to weldability.

Small-scale weldments of sample steels selected by means of evaluation of previous base metal and CTS test results were produced and tested.

BASE MATERIAL SELECTION

On the basis of commercial availability, the target properties of the candidate steels as manufactured by thermomechanical rolling and on-line cooling are as follows:

Target Properties

| <u>Candidate Steel Source</u> | <u>Thickness, in inches</u> | <u>Minimum Yield Strength, in ksi</u> | <u>Minimum Charpy V-Notch, in ft-lb</u> | <u>Maximum IIW Carbon Equivalent</u> |
|-------------------------------|-----------------------------|---------------------------------------|---|--------------------------------------|
| A | 1.25 | 65 | 100 at -75C | 0.40 |
| B* | 2.00 | 65 | 100 at -75C | 0.40 |
| C | 2.00 | 80 | 30 at -60C | 0.50 |
| D | 2.00 | 100 | 30 at -60C | 0.60 |

* replaced by 80 ksi yield strength conventional quenched and tempered steel

TESTING PROCEDURES

Chemical Analysis

The composition of the four candidate steels and the two HY steels used in the weldability test (see Weldability Test below) was determined.

Metallography

The micro-structure and austenitic grain size were determined for each candidate steel at three locations: surface, quarter-thickness, and mid-thickness.

Mechanical Testing

1. Tensile Test: Longitudinal and transverse tensile properties were determined with 1/2" diameter, 2" gage length specimens removed from the quarter-thickness location.

2. Charpy V-Notch Test: Longitudinal and transverse Charpy V-Notch impact properties were determined with standard-sized specimens removed at three locations: surface, quarter-thickness, and mid-thickness.

3. NDT Drop Weight Test: The NDT temperature was determined with 5/8" thickness specimens with the weld bead located at the plate surface for all steels, at the quarter-thickness location for Steels B/C/D, and at the mid-thickness location for Steel A.

4. Dynamic Tear Test: The dynamic tear energy was determined with longitudinal 5/8" thickness specimens removed from the plate surface.

5. Hardness Survey: A through-thickness hardness survey was conducted for each candidate steel.

Weldability Test

Preliminary data concerning the weldability of the four candidate steels was obtained on the basis of Controlled Thermal Severity (CTS) tests (2). The data is presented as a HAZ cracking rating: i.e., the number of HAZ cracks observed by 100X examination of four metallographic sections taken through each test weld. Each test assembly consisted of one bithermal weld (thermal severity number of 16) and one trithermal weld (thermal severity number of 24). In general, two test assemblies were used for each evaluation. The pertinent welding parameters are shown in Table C1. For comparison purposes, CTS tests were conducted with HY80 and HY100 steels.

Small Scale Weldment Test

Steels A and C were selected for welding (by SMAW) and testing of small-scale weldments. The pertinent welding parameters are shown in Table C2. Testing consisted of transverse tensile, Charpy V-Notch and hardness at the quarter-thickness where practicable.

RESULTS

The results of tests are shown as follows:

| | |
|---------------------------|--|
| Chemical Composition | : Table One |
| Metallography | : Table Two and Figures One through Three |
| Tensile Properties | : Table Three and Tables B1/B2 |
| Charpy V-Notch Properties | : Figures Four through Seven and Tables B3/B4/B5 |
| NDT Temperature | : Table Four |
| Dynamic Tear Properties | : Figure Eight and Table B6 |
| Hardness Survey | : Figure Nine and Table B7 |
| CTS Test | : Table Five |
| Small-Scale Weldment | : Tables Six through Eight |

DISCUSSION OF RESULTS

Steel A

1. Composition: Steel A is a microalloyed carbon-manganese steel with a very low carbon content (0.04%). The microalloying elements present are columbium, titanium and boron. The carbon equivalent (0.32) easily met the target value, 0.40 maximum.

2. Metallography: The average McQuaid-Ehn austenitic grain size was eight (8). The accepted requirement for fine grain steel is five (5) or finer. Determinations taken at the mid-thickness indicated a grain size of seven (7), slightly coarser than at other locations.

The microstructure consisted of bainite and ferrite as shown at Figure 1, 500X magnification. The microstructure was uniform through the thickness of the plate. The sulfide inclusions were spheroidal, typical of shape-control processing.

3. Tensile Properties: The yield strength determined for the longitudinal and transverse orientations met the target value of 65 ksi minimum. The transverse tensile and yield strength determinations were somewhat higher than the values determined in the longitudinal orientation. The reason for this is not apparent.

4. Charpy Impact Properties: Steel A showed a lower bound Charpy V-Notch temperature transition between approximately -100F and -120F. The lower bound curve indicates that the steel met the target value of 100 ft-lbs at -75C (-103F). The lower bound was comprised of data points from all (three) locations, in contrast with Steels C and D where

the lower bound was defined almost exclusively by surface data. It is interesting to note that Steel A has been accelerated cooled, while Steels C and D have been directly quenched and tempered. The upper shelf data was over 170 ft-lbs.

The Charpy V-Notch data meets the AES MODU requirement for special application service at -30C, i.e., 25 ft-lbs at -60C.

5. NDT Drop Weight Test: The (NDT) temperature was -65C (-85F) at the plate surface. This temperature corresponds to the near upper shelf regime for Charpy V-Notch and to the transition range for dynamic tear. The mid-thickness NDT temperature was slightly lower, -75C (-103F), and corresponds to the dynamic tear lower shelf.

6. Dynamic Tear Test: Steel A exhibited dynamic tear energies over 1100 ft-lbs at temperature down to -60C, where a very steep transition occurred. The transition range correlated with the surface nil-ductility transition temperature as determined by the drop-weight test.

7. Hardness Survey: Steel A showed minor variations in hardness on a through thickness traverse. The hardness ranged from 93 to 98 in the Rockwell B Scale. The value of 98 was recorded only at the plate surface.

8. CTS Test: No CTS testing was conducted for Steel A, 1-1/4" thickness, in that the yield strength and the thickness did not permit correlation to the HY80/100, 2" thickness, used for a comparison basis, and a steel of comparable yield strength and thickness was not available.



FIGURE 1
Steel A: 500X, 2% Nital etch

9. Small Scale Weldment: Steel A exhibited generally satisfactory although somewhat irregular results. The tensile strength was approximately 4-1/2% below that previously recorded for the base metal; however, it was noted that the fracture occurred in the weld metal and not in the base metal. With the exception of one fusion-line specimen the Charpy V-Notch impact data met the ABS MODU requirement for weldments for special application service at -30C; i.e., 17 ft-lb at -60C. The Charpy V-Notch impact data was somewhat lower (especially two fusion-line specimens) than the previously determined base metal data indicating a degrading effect of the heat of welding. Subsequent metallurgical examination indicated that the fracture path for the 10 ft-lb specimen was contained wholly within the weld metal adjacent to the fusion line, and that the fracture path for the 17 ft-lb specimen generally followed the fusion line although it did at some locations pass solely through the weld metal adjacent to the fusion line.

The above results suggest that the low tensile strength and Charpy V-Notch impact values recorded for Steel A were resultant from the weld metal characteristics and did not indicate substandard performance of Steel A in the small scale weldment test. The Vickers Hardness data showed no abnormally high hardness values.

Steel B

As previously noted, Steel B is an 80 ksi yield strength quenched and tempered steel which has been used as a substitute for the originally intended 65 ksi yield strength thermomechanically processed steel. The test results are evaluated in terms of 80 ksi yield strength target properties noted in BASE MATERIAL SELECTION as Candidate Steel C.

1. Composition: Steel B is a low carbon (0.10%) conventional quenched and tempered carbon-manganese-molybdenum steel with a high manganese content (1.84%). Columbium is present as a microalloying addition. The carbon equivalent (0.50) met the target value, 0.50 maximum.

2. Metallography: The average McQuaid-Ehn austenitic grain size was seven (7). The accepted requirement for fine grain steel is five (5) or finer. Determinations taken at three thickness locations indicated that a grain size gradient extended from the surface to the mid-thickness where the smallest grain size, eight (8), was observed.

The microstructure consisted of tempered martensite as shown in Figure 2, 500X magnification. No significant differences were noted among the microstructures at the three locations: surface, quarter-thickness, and mid-thickness. The sulfide inclusions were spheroidal, typical of shape-control processing.

3. Tensile Properties: The yield strength determined for the longitudinal and transverse orientations met the target value of 80 ksi minimum. The ductility parameters were satisfactory. Steel B met the tensile requirements for HY80.

4. Charpy Impact Properties: The lower bound Charpy V-Notch data met the target value, 30 ft-lbs at -60C (-76F).

Extrapolation of the lower bound to 0F (testing higher than -40F was not conducted) indicates that Steel B also meets one requirement for HY80, 60 ft-lbs at 0F. In addition, the transverse/mid-thickness data meets the second requirement for HY80, 35 ft-lbs at -120F specified for specimens of transverse orientation and mid-thickness location (for plate thicknesses 7/8" and over). It should be noted, however, that data from many surface/longitudinal and quarter-thickness/longitudinal specimens developed less than 35 ft-lbs when tested at -120F.



FIGURE 2
Steel B: 500X, 2% Nital etch

The Charpy V-Notch data meets the ABS MODU requirement for special application service at -30C, i.e., 25 ft-lbs at -60C.

5. NDT Drop Weight Test: The (NDT) temperature was -45C (-49F) for the plate surface and also for the quarter-thickness location. This temperature corresponds to the near upper shelf regime of Charpy V-Notch data; the lower bound value at the NDT temperature is approximately 100 ft-lbs. The NDT temperature is within the transition for the dynamic tear data.

6. Dynamic Tear Test: Steel B exhibited dynamic tear energies over 1100 ft-lbs at temperature down to -20C (-4F), where a gradual transition commenced. The approximate mid-point of the transition range correlated with the nil-ductility transition temperature. The dynamic tear data, 800 ft-lbs at -40F, indicates that Steel B will meet the requirement for HY80, 450 ft-lbs at -40F.

7. Hardness Survey: With the exception of several high values at one surface of the plate, Steel B exhibited a relatively uniform through thickness hardness ranging from 96 to 98 in the Rockwell B Scale. High values of Rockwell C Scale 27 (approximately 103 in the Rockwell B Scale) were recorded at one surface of the plate; this could be resultant from higher quenching rates at this surface.

8. CTS Test: Steel B demonstrated greater resistance to HAZ cracking than the baseline HY80 steel when welded in the controlled thermal severity (CTS) test. No HAZ cracking (i.e., a crack rating of zero) was noted for the bi-thermal test weld with a thermal severity number (TSN) of 16. In comparison, the baseline HY80 showed a HAZ cracking rating of one (1). For the tri-thermal test weld (TSN = 24), Steel B developed a HAZ cracking rating of one (1), while the baseline HY80 exhibited a HAZ cracking rating of four (4).

Steel C

Steel C was submitted as an 80 ksi yield strength steel. Testing indicated that this steel is a 100 ksi yield strength steel. The test results are evaluated in terms of both 80 ksi and 100 ksi yield strength requirements.

1. Composition: Steel C is a low carbon (0.12%) thermomechanically processed steel. The principal alloying elements are manganese, nickel, chromium and molybdenum. Vanadium and boron are present as microalloying additions. The carbon equivalent (0.49) met the target values for 80 ksi yield strength (0.50 maximum) and 100 ksi yield strength (0.50 maximum).

2. Metallography: The average McQuaid-Ehn austenitic grain size was six (6). The accepted requirement for fine grain steel is five (5) or finer. At the mid-thickness location, the grain size was seven (7), slightly finer than at other locations.

The microstructure consisted of tempered bainite and martensite, as shown at 500X magnification in Figure 3. The microstructure was uniform through the thickness of the plate. The sulfide inclusions were spheroidal, typical of shape-control processing.

3. Tensile Properties: The yield strength determined for the longitudinal and transverse orientation was 106 ksi. This strength met the target property for 100 ksi yield strength steel. The ductility data was satisfactory. Steel C met the tensile requirements for HY100; however, the yield strength exceeded the upper limit of the yield strength range specified for HY80, 99.5 ksi.

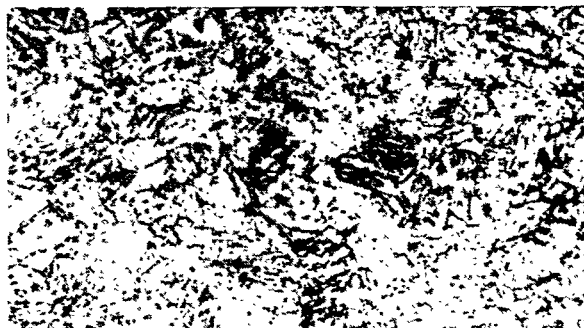


FIGURE 3

Steel C/D: 500X, 2% Nital etch

4. Charpy Impact Properties: The lower bound Charpy V-Notch data met the target value, 30 ft-lbs at -60C (-76F), and met the impact requirements for HY80/100. The Charpy V-Notch data also meets the ABS MODU requirement for special application service at -30C, i.e., 25 ft-lbs at -60C.

The lower bound is defined exclusively by transverse specimens removed from the plate surface. In addition, longitudinal/surface data generally represents the lower bound for specimens of longitudinal orientation. The data suggests that the surface toughness is less than the toughness for other plate locations. This is not interpreted as being detrimental in that all Charpy V-Notch toughness values were quite high and met requirements and the target values.

5. NDT Drop Weight Test: The NDT temperature was determined for the plate surface and the quarter-thickness. The results suggested that the fracture toughness properties of the plate surface are different and lower than those of the quarter thickness. The surface NDT temperature was -29C (-20F) while the quarter-thickness NDT temperature was -75C (-103F).

6. Dynamic Tear Test: Steel C exhibited dynamic tear energy over 1100 ft-lbs at temperature down to -50C (-58F), where a sharp transition commenced. The dynamic tear data indicates that Steel C will meet the requirements for HY80/100: at -40F, 450 ft-lbs (for HY80) and 500 ft-lbs (for HY100).

7. Hardness Survey: The hardness traverse data was uniform ranging from 21 to 23 in the Rockwell C Scale. No significant variation in tensile strength through thickness of the plate is indicated.

8. CTS Test: The CTS test results for Steel C were superior to the results for both baseline materials, HY80 and HY100. Steel C developed HAZ cracking ratings of one-half (1/2) for the bithermal test weld (TSN = 16) and for the trithermal test weld (TSN = 24).

9. Small Scale Weldment: Steel C exhibited satisfactory results. The tensile strength was equivalent to that determined previously for the base metal. All Charpy V-Notch impact data met the ABS MODU requirement for weldments for special application service at -30C; i.e., 17 ft-lbs at -60C. The Charpy V-Notch impact data was somewhat lower (especially two fusion-line specimens) than the previously determined base metal data, indicating a degrading effect of the heat of welding. The Vickers Hardness data showed no abnormally high hardness values.

Steel D

Steel D was submitted as a 100 ksi yield strength steel. Testing indicated that this steel is a 120 ksi yield strength steel. For comparison purposes, the criteria and requirements for 100 ksi yield strength steel are used.

1. Composition: Steel D is a low carbon (0.11%) thermomechanically processed steel. The principal alloying elements are manganese, nickel, chromium and molybdenum. Vanadium and boron are present as microalloying additions. The carbon equivalent (0.51) easily met the target value for 100 ksi yield strength (0.60 maximum).

2. Metallography: The average McQuaid-Ehn austenitic grain size was six (6). The accepted requirements for the fine grain steel is five (5) or finer. No variation with thickness location was noted.

The microstructure consisted of tempered bainite and martensite, as shown at 500X magnification in Figure 3. The microstructure was uniform through the thickness of the plate. The sulfide inclusions were spheroidal, typical of shape-control processing.

3. Tensile Properties: The yield strength determined for the longitudinal and transverse orientations was 124 ksi and 122 ksi, respectively. These values met the target values of 100 ksi, but exceeded the upper limit of the yield strength specified for HY100, 115 ksi. The ductility data was satisfactory.

4. Charpy Impact Properties: In general, the Charpy V-Notch data met the target value, 30 ft-lbs at -60C (-76F). The transverse/mid-thickness data met the HY100 requirements, 30 ft-lbs at -120F and 55 ft-lbs at 0F, which are specified for specimens of transverse orientation and mid-thickness location (for plate thicknesses 7/8" and over). It should be noted, however, that data from the transverse/surface developed less than 30 ft-lb when tested at -120F. For information, the Charpy V-Notch transverse/mid-thickness data meets the requirements for HY130, i.e., (1) 60 ft-lbs minimum at 0F, (2) and at 70F, a maximum of the 0F data value plus 15 ft-lbs. The Charpy V-Notch data also meets the ABS MODU requirement for 100 ksi yield strength steel for special application service at -30C, i.e., 25ft-lbs at -60C.

The lower bound is defined almost exclusively by transverse specimens removed from the plate surface; at -120F the value was less than 10 ft-lbs. In addition, longitudinal/ surface data generally represents the lower bound for specimens of longitudinal orientation.

The data suggests that the surface toughness is less than the toughness for other plate locations. It is further noted that this lower-toughness surface effect, which for Steels C and D defines the lower bound, is more severe for Steel D than for Steel C in terms of absolute values and in terms of percentage decrease below the average data plots. This suggests that the severity of the surface effect increases with increasing yield strength.

5. NDT Drop Weight Test: The NDT temperature for the surface was -29C (-20F); the NDT temperature for the quarter-thickness was -35C (-67F). The surface NDT temperature corresponds to the transition ranges of the Charpy V-Notch impact lower bound data and the dynamic tear data. The lower bound Charpy V-Notch data at the NDT temperature is approximately 40 ft-lbs. The dynamic tear energy at the NDT temperature is approximately 400 ft-lbs. The quarter-thickness NDT temperature corresponds to the upper transition of the Charpy V-Notch impact non-surface data. The difference in the NDT temperatures again suggests that the surface of the plate has a lower toughness than the quarter-thickness location.

6. Dynamic Tear Test: Steel D exhibited dynamic tear energy over 1100 ft-lbs at temperature down to 0C (32F), where a gradual transition commenced. The dynamic tear data did not meet the requirements for HY100, 450 ft-lbs at -40F; however, the specimens tested were longitudinal/surface and probably developed a lower absorbed energy than the specified transverse/mid-thickness specimens. For information, the dynamic tear data indicates that Steel D will meet the requirement for HY130, 500 ft-lbs at 0F.

7. Hardness Survey: The hardness traverse data ranged from 24 to 29 in the Rockwell C Scale. With the exception of several readings of R_c 25 near the mid-thickness of the plate and one high value of R_c 29, the hardness was uniform ranging from 26 to 28 in the Rockwell C Scale.

8. CTS Test: The CTS test results for Steel D were superior to the results for both baseline materials, HY80 and HY100. Steel D developed a HAZ cracking rating of one-half (1/2) for the tri-thermal test weld (TSN = 24); no cracking was developed for the bithermal test weld.

Mechanical Property Correlations

1. Strength and Toughness: The thermomechanically processed steels A/C/D exhibit a decrease in toughness as the yield strength increases. This is shown by the dynamic tear energy-temperature transition (Figure 8) where the dynamic tear curve shifts to the right with increasing yield strength. The inverse relationship of toughness and yield strength is generally valid for steels that are not vastly different in chemistry. Thus, it is interesting to note that the dynamic tear curve for the conventionally processed quenched and tempered Steel B generally falls with the curve for the thermomechanically processed Steel C, although

the yield strength of Steel C is over 20 ksi higher than the yield strength of Steel B. This data suggests that the toughness of thermomechanically processed steel is superior to that of an equivalent strength conventionally processed steel.

A comparison of the Charpy V-Notch impact absorbed energy-temperature transition (Figures 5 and 6) for Steels B and C illustrates that although the energy at -40C is approximately equivalent, the Steel C transition commences at lower temperature than for Steel B. This indicates a superior low temperature toughness, which is also indicated by the lower NDT temperature for Steel C (-103F) than for Steel B (-49F). It should be noted that the above comparisons are based upon "non-surface" data for Steel C, i.e., data from the quarter thickness and from the mid-thickness, and all data for Steel B.

2. NDT, Dynamic Tear and Charpy V-Notch: In general, there was not good correlation among the toughness data for the thermomechanically processed steels A/C/D. NDT temperature specimens prepared and tested in accordance with ASTM E208 demonstrate that the NDT temperatures are too high for classical correlation to dynamic tear energy-temperature transitions where the NDT temperature corresponds to the lower shelf (4). Comparisons with Charpy V-Notch impact energy-temperature transition also show that the NDT temperatures are too high; although correlation is better with the lower bound curve for Steel D where the lower bound curve is defined by surface specimens. The upper shelf NDT/CVN correlation is documented in the literature (3) although for steels with considerably higher yield strengths.

A more classical correlation between NDT and dynamic tear lower shelf was demonstrated with drop weight specimens prepared with the tension surface and crack-starter weld bead located at the quarter-thickness of the plate or at the mid-thickness of the plate. These results, i.e., a lowering of the NDT temperature, were anticipated based upon comparison of surface and non-surface Charpy V-Notch impact data which indicated a lower-toughness surface effect (previously discussed in "Charpy Impact Properties" for Steel C and "Charpy Impact Properties" for Steel D). For Steel C, the absolute value for the Charpy V-Notch absorbed energy for the non-surface data at the quarter-thickness NDT temperature and for the lower bound (surface data) at the surface NDT temperature is very similar, approximately 115 ft-lbs. This value is much higher than that generally reported for indexing an NDT/CVN correlation (4)(5). Steel D did not exhibit a CVN correlation similar to Steel C.

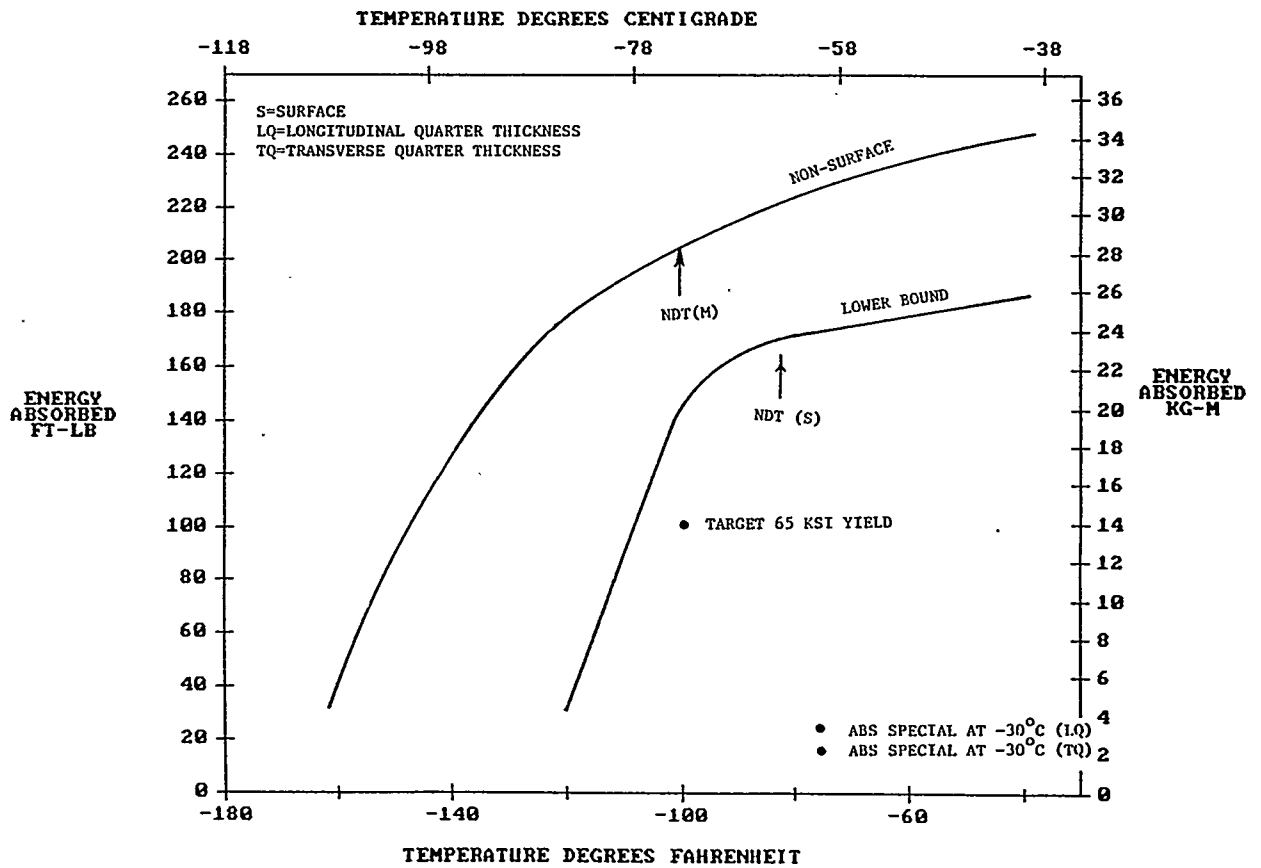


FIGURE FOUR STEEL A
CHARPY U-NOTCH ABSORBED ENERGY
TEMPERATURE TRANSITION

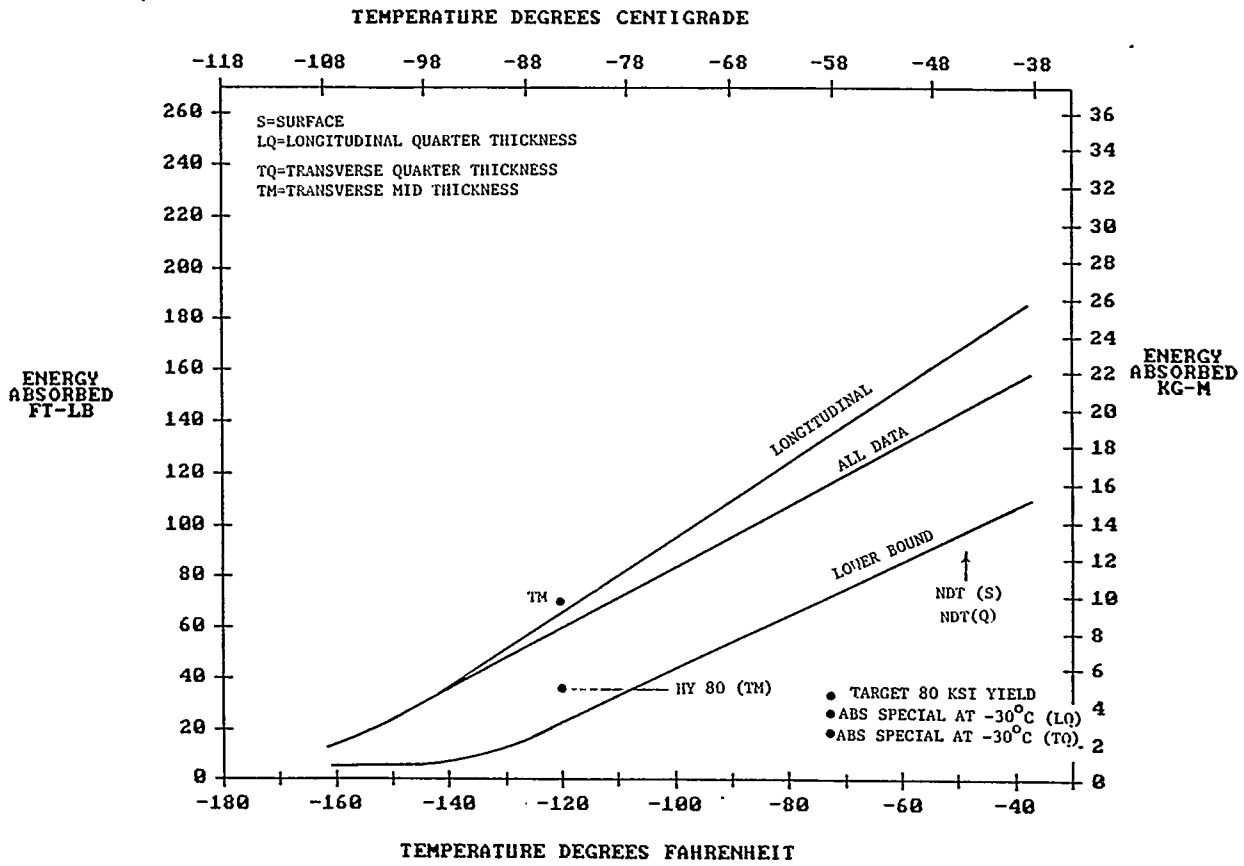


FIGURE FIVE STEEL B
CHARPY U-NOTCH ABSORBED ENERGY
TEMPERATURE TRANSITION

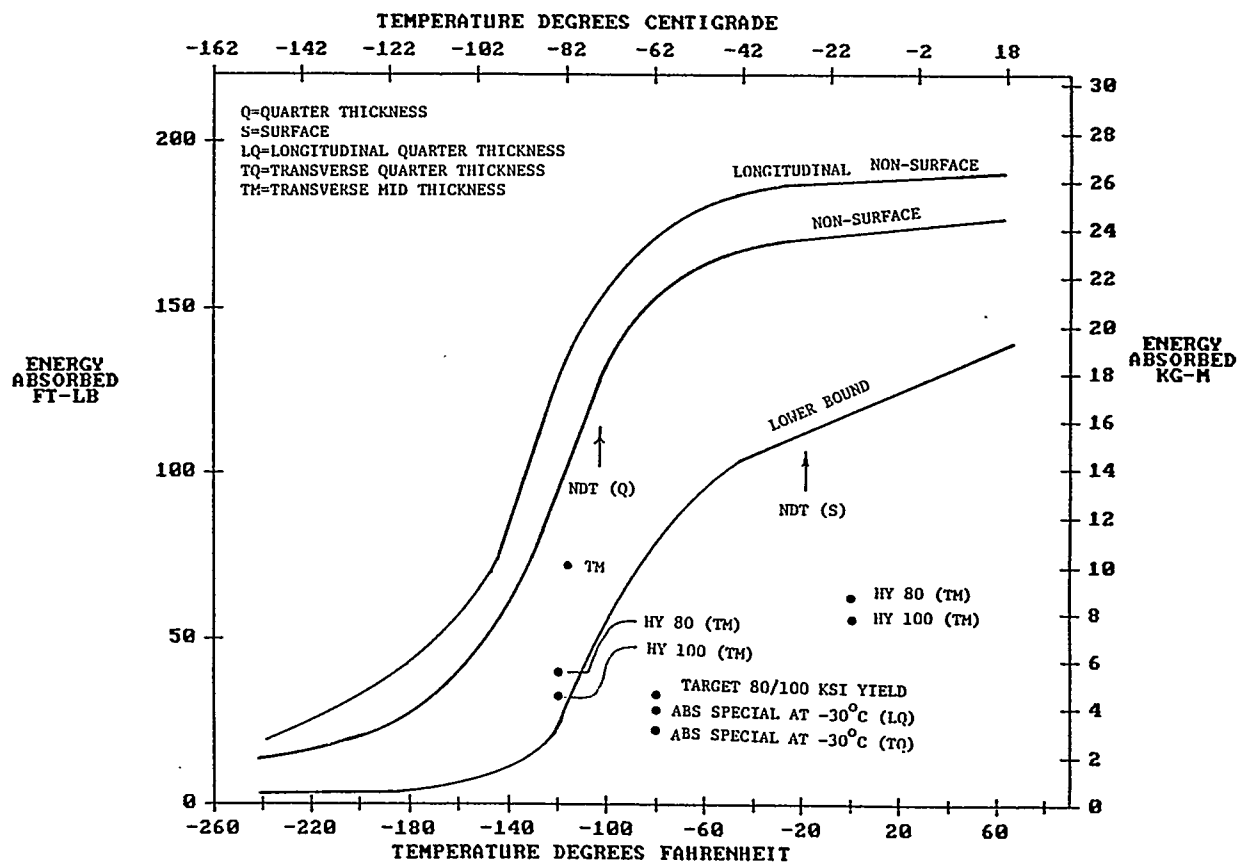


FIGURE SIX STEEL C
CHARPY U-NOTCH ABSORBED ENERGY
TEMPERATURE TRANSITION

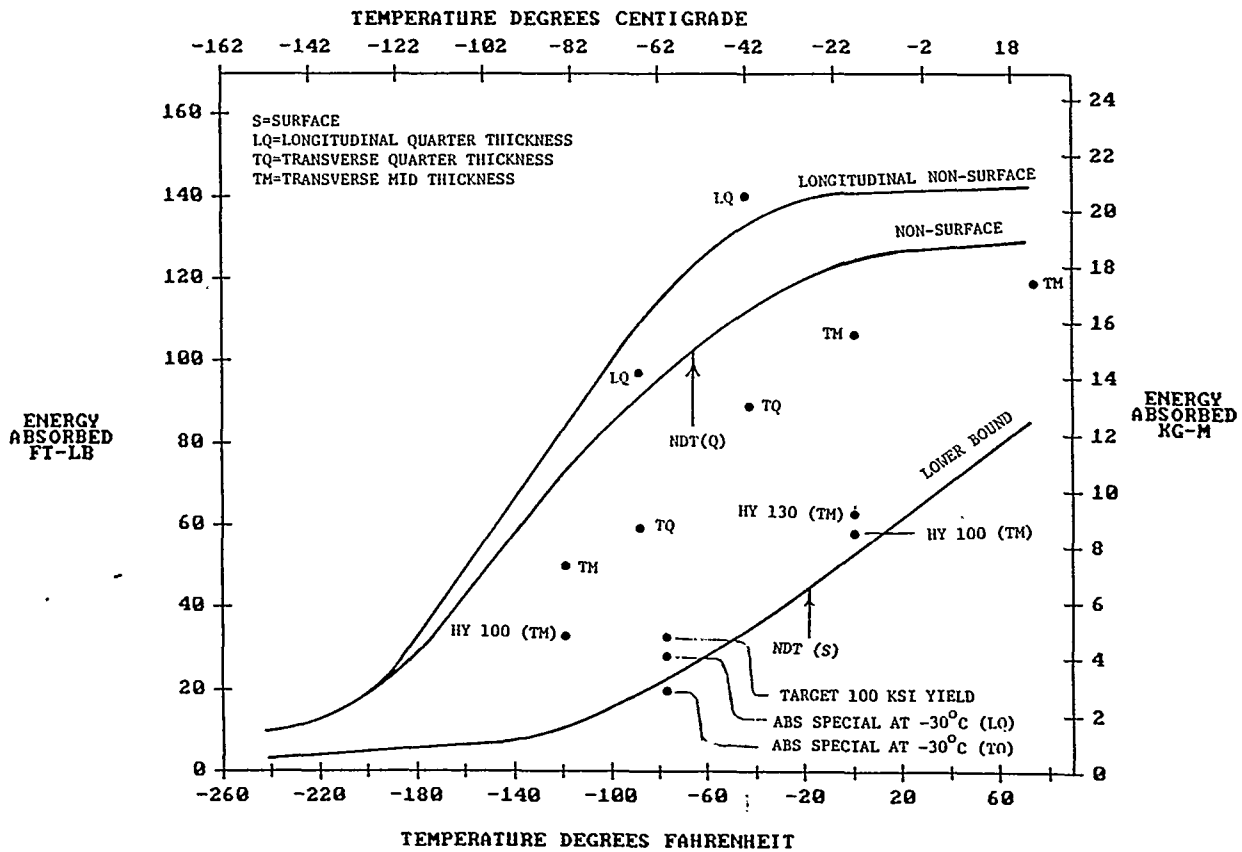


FIGURE SEVEN STEEL D
CHARPY U-NOTCH ABSORBED ENERGY
TEMPERATURE TRANSITION

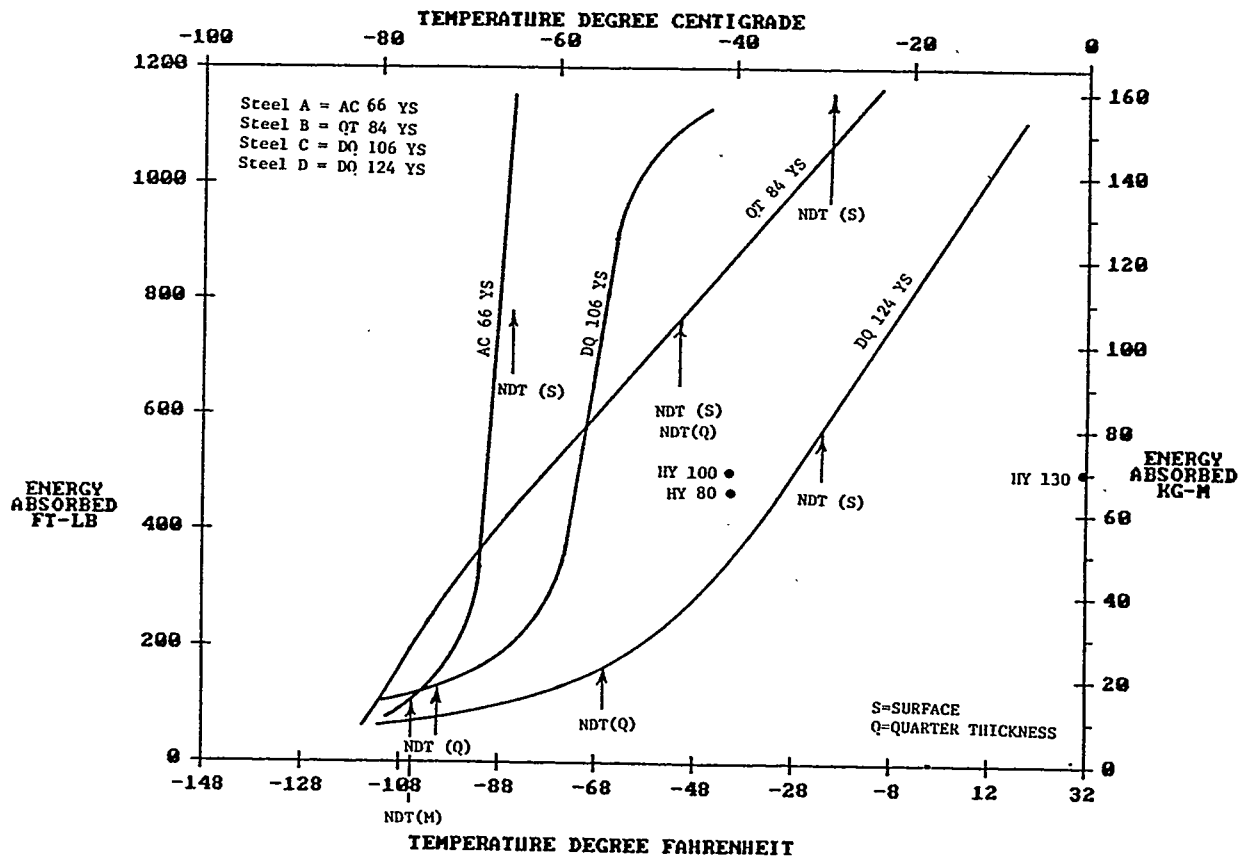


FIGURE EIGHT STEEL A THROUGH D
DYNAMIC TEAR ABSORBED ENERGY
TEMPERATURE TRANSITION

Review of all the Charpy V-Notch impact test results, including absorbed energy, lateral expansion and fracture appearance, indicated that the thermomechanically processed Steels C/D displayed a lower-toughness surface effect while the conventionally processed quenched and tempered Steel (B) did not exhibit this effect.

CONCLUSIONS AND RECOMMENDATIONS

On the basis of this study and the results obtained, the following conclusions are drawn.

1. All steels studied satisfied the base metal toughness requirements for ABS MODU special application service at -30C.

2. Steel B met (dynamic tear test data indicates likely compliance with specification requirements) the small-scale mechanical test requirements for HY80.

3. Steel C met (dynamic tear test data indicates likely compliance with specification requirements) all (except the HY80 upper limit on yield strength) the small scale mechanical test requirements for HY80 and HY100, indicating a potential as a substitute for HY steels.

4. In the 80 ksi to 100 ksi yield strength range, the thermomechanically processed steel exhibited higher toughness than the conventionally processed quenched and tempered steel.

5. Steels B/C/D exhibited greater resistance to HAZ cracking than HY80/100.

6. Steels A/C exhibited good weldability and generally met the ABS MODU requirements for special application service at -30C.

7. The thermomechanically processed steels exhibited a lower toughness associated with the surface in comparison

with other locations. This lower-toughness surface effect was more evident in the direct quenched and tempered steels (C/D).

It is recommended that thermo-mechanically processed steels of the type evaluated herein can be considered for higher strength applications requiring high toughness and for higher strength applications at lower temperature. This recommendation includes further evaluation encompassing explosion bulge testing, line-heating, cold forming and high heat input welding.

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TABLE ONE
CHEMICAL COMPOSITION, IN PERCENT
IIW CARBON EQUIVALENT

| ELEMENT | STEEL A | STEEL B | STEEL C | STEEL D | ABS MODU FQ GRADES(1) | CTS TEST CONTROLS | | MIL-S-16216J | |
|------------|---------|---------|---------|---------|--------------------------|----------------------|--------|--------------|-----------|
| | | | | | | HY80 | HY100 | HY80 | HY100 |
| Carbon | 0.04 | 0.10 | 0.12 | 0.11 | 0.18 max | 0.16 | 0.17 | 0.10-0.20 | 0.10-0.22 |
| Manganese | 1.43 | 1.84 | 1.01 | 0.94 | 1.60 max | 0.35* | 0.33* | 0.10-0.45 | 0.10-0.45 |
| Silicon | 0.17 | 0.21 | 0.27 | 0.26 | 0.55 max | 0.21* | 0.16* | 0.12-0.38 | 0.12-0.38 |
| Phosphorus | 0.019 | 0.012 | 0.010 | 0.014 | 0.025 max | 0.14 | 0.016 | 0.020 max | 0.020 max |
| Sulfur | 0.003 | 0.005 | 0.003 | 0.003 | 0.025 max | 0.017 | 0.020 | 0.020 max | 0.020 max |
| Nickel | 0.23 | 0.05 | 0.78 | 1.05 | (2) | 2.67* | 2.71* | 2.43-3.32 | 2.67-3.57 |
| Chromium | 0.04 | 0.10 | 0.45 | 0.45 | (2) | 1.61* | 1.49* | 1.29-1.86 | 1.29-1.86 |
| Molybdenum | 0.01 | 0.31 | 0.23 | 0.33 | (2) | 0.43* | 0.36* | 0.27-0.63 | 0.27-0.63 |
| Copper | 0.25 | 0.10 | 0.23 | 0.23 | (2) | 0.04* | 0.10* | 0.25 max | 0.25 max |
| Aluminum | 0.032 | 0.046 | 0.018* | 0.049* | — | 0.017* | 0.005* | NS | NS |
| Columbium | 0.028 | 0.029 | 0.005* | 0.005* | (2) | 0.005* | 0.005* | NS | NS |
| Vanadium | 0.005* | 0.005* | 0.038 | 0.048 | (2) | 0.008* | 0.005* | 0.03 max | 0.03 max |
| Titanium | 0.018 | 0.005* | 0.005* | 0.005* | — | 0.005* | 0.005* | 0.02 max | 0.02 max |
| Boron | 0.0011 | 0.001* | 0.0011 | 0.0012 | (2) | 0.001* | 0.001* | NS | NS |
| Nitrogen | 0.0026 | 0.008* | 0.005* | 0.005* | — | 0.003* | 0.007* | NS | NS |

| | | | | | | | | | |
|--------|------|------|------|------|--|------|------|----------------------|----------------------|
| IIW-CE | 0.32 | 0.50 | 0.49 | 0.51 | | 0.81 | 0.78 | 1.02 max 0.59 min | 1.05 max 0.61 min |
|--------|------|------|------|------|--|------|------|----------------------|----------------------|

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

NS = Not Specified

(1) Alloying and fine-grain elements are to be reported.

(2) Are to be reported, including zirconium.

*By spectrographic analysis

TABLE TWO
AUSTENETIC GRAIN SIZE (1)

| <u>SAMPLE</u> | <u>SURFACE</u> | <u>QUARTER THICKNESS</u> | <u>MID THICKNESS</u> |
|---------------|----------------|------------------------------|--------------------------|
| Steel A | 8 | 8 | 7 |
| Steel B | 6 | 7 | 8 |
| Steel C | 6 | 6 | 7 |
| Steel D | 6 | 6 | 6 |

- (1) A grain size of five or finer (i.e., higher number) fulfills the requirements for "Fine Grain".

TABLE THREE
AVERAGE TENSILE PROPERTIES
LONGITUDINAL (TRANSVERSE)

| <u>SAMPLE</u> | <u>TENSILE STRENGTH, IN KSI</u> | <u>YIELD STRENGTH, IN KSI</u> | <u>ELONGATION GL = 4.51 A, IN PERCENT</u> | <u>REDUCTION OF AREA, IN PERCENT</u> |
|---------------|---|---------------------------------------|---|--|
| Steel A | 91.5 (95.0) | 66.0 (70.0) | 28 (26) | 74 (76) |
| Steel B | 98.0 (97.0) | 84.0 (84.0) | 25 (24) | 76 (72) |
| Steel C | 114 (114) | 106 (106) | 24 (21) | 76 (72) |
| Steel D | 130 (130) | 124 (122) | 20 (20) | 70 (67) |

Note: Data for Steels B/C/D (2 inches in thickness) is from quarter thickness.
Data for Steel A (1½ inches in thickness) is from quarter thickness
thru mid thickness.

TABLE FOUR
NIL-DUCTILITY TRANSITION TEMPERATURE

| <u>SAMPLE</u> | <u>TEST LOCATION</u> | <u>IN DEGREES CENTIGRADE</u> | <u>IN DEGREES FAHRENHEIT</u> |
|---------------|--------------------------|----------------------------------|----------------------------------|
| Steel A | Surface | -65 * | -85 |
| Steel A | Mid Thickness | -75 * | -103 |
| Steel B | Surface | -45 * | -49 |
| Steel B | Quarter Thickness | -45 * | -49 |
| Steel C | Surface | -29 | -20 * |
| Steel C | Quarter Thickness | -75 * | -103 |
| Steel D | Surface | -29 | -20 * |
| Steel D | Quarter Thickness | -55 * | -67 |

*Temperature scale used in test.

TABLE FIVE
CONTROLLED THERMAL SEVERITY (CTS) TEST
HAZ CRACKING RATING

| <u>SAMPLE</u> | <u>BITHERMAL</u> <u>TSN = 16</u> | <u>TRITHERMAL</u> <u>TSN = 24</u> |
|---------------|-------------------------------------|--------------------------------------|
| Steel B | 0 | 1 |
| Steel C | $\frac{1}{2}$ | $\frac{1}{2}$ |
| Steel D | 0 | $\frac{1}{2}$ |
| HY80 | 1 | 4 |
| HY100 | 2 | 1 |
| HY80 (1) | 2 | 3 |

(1) Data from Stern/Quattrone (Ref. 2).

TABLE SIX
WELDMENT TRANSVERSE TENSILE (1/4 T) DATA

| <u>SAMPLE</u> | <u>TENSILE STRENGTH,</u> <u>IN KSI</u> | <u>LOCATION</u> <u>OF FRACTURE</u> |
|---------------|---|---------------------------------------|
| STEEL A | 88.0 86.0 | WELD METAL WELD METAL |
| STEEL C | 114 114 | BASE METAL BASE METAL |

TABLE SEVEN
WELDMENT TRANSVERSE CHARPY V-NOTCH (1/4 T) DATA,
IN FOOT-POUNDS AT -75F (-60C)

| <u>SAMPLE</u> | <u>FUSION LINE</u> | <u>1mm HAZ</u> | <u>3mm HAZ</u> |
|---------------|--------------------|-------------------|-------------------|
| STEEL A | 10 17 132 | 148 144 74 | 166 178 149 |
| STEEL C | 155 60 54 | 155 118 114 | 120 165 166 |

TABLE EIGHT
WELDMENT TRANSVERSE HARDNESS SURVEY (1/4 T) DATA
IN VICKERS HARDNESS NUMBER

| <u>LOCATION</u> | <u>STEEL A</u> | <u>STEEL C</u> |
|--------------------------------------|----------------|----------------|
| WELD METAL CENTERLINE | 223 | 250 |
| FUSION LINE | 237 | 265 |
| DISTANCE FROM FUSION LINE, IN mm: | | |
| 1 | 211 | 239 |
| 2 | 191 | 226 |
| 3 | 182 | 256 |
| 4 | 195 | 248 |
| 5 | 202 | 243 |

APPENDIX A

COMMENTARY ON METALLURGICAL PROCESSING

Three of the four steels investigated herein have been produced by thermomechanical processing. Through thermomechanical processing, steel can be produced to levels of toughness and strength usually achieved by a separate heat treatment subsequent to rolling. A leaner chemistry without loss of strength is possible, thus reducing the carbon equivalent with an attendant increase in weldability (A1). Economic benefits are derived from lower alloying costs and omission of heat treatment (A2).

Thermomechanical processing is an extension of the controlled rolling technology, a viable commercial practice for more than fifteen (15) years. The basic change from controlled rolling methodology is the rolling of the steel at lower temperature, specifically around the A_r3 temperature. Thermomechanical processes are proprietary, and as such, show differences in the number of rolling stages and the reduction ratio of each stage, the temperature regimes of the rolling stages, and the use or omission of accelerated cooling or direct quench and tempering after rolling. The use of accelerated cooling or direct quench and tempering after thermomechanical rolling permits steel chemistries of much lower carbon equivalent without loss of strength properties (A2). In addition, some proprietary processes may include substantial intermediate reheating and continued rolling (A3).

In light of the proprietary differences inherent to the thermomechanical processing of steel, several generalizations as to the process can be made and are listed below:

1. The slab reheat temperature is generally lower than for conventional steel rolling practice; reheat in the range of 950-1200C (1742-2192F) provides a finer initial austenitic grain size at the beginning of rolling than the higher temperature of conventional practice (A4).

2. The subsequent rolling stages consist of high reductions in the austenite recrystallization region to promote a finer austenitic grain size, and high reductions in the austenite non-recrystallization region but above the austenite transformation temperature to promote deformation bands for subsequent fine grain nucleation (A4, A5). In addition to the above rolling stages, rolling may also be conducted just above the A_r3 and at times below the A_r3 after which the steel is air cooled (A4, A5, A6, A7).

3. Depending upon the desired properties, the rolled steel is air cooled, accelerated cooled, or direct quenched and tempered. Generally, the cooling rates for accelerated cooling are less than 15C per second, while for direct quenching they are higher (A8, A9, A10).

The cooling practices used for the thermomechanically processed steels tested herein are as follows:

Steel A: Accelerated Cooled
Steel C: Direct Quenched and Tempered at 640C (1184F)
Steel D: Direct Quenched and Tempered at 600C (1112F)

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APPENDIX B - TEST DATA

TABLE B1

BASE METAL LONGITUDINAL TENSILE PROPERTIES

| SAMPLE | TENSILE STRENGTH IN KSI | YIELD STRENGTH IN KSI | ELONGATION GL = 4.51 A, IN PERCENT | REDUCTION OF AREA IN PERCENT |
|---------|-------------------------------|-----------------------------|--|---------------------------------|
| Steel A | 91.0, 91.5 | 66.0, 66.0 | 27, 29 | 74, 74 |
| Steel B | 97.0, 98.0 | 83.5, 84.5 | 24, 26 | 77, 75 |
| Steel C | 114, 113 | 106, 106 | 23, 24 | 76, 76 |
| Steel D | 130, 131 | 123, 124 | 20, 20 | 72, 69 |

TABLE B2

BASE METAL TRANSVERSE TENSILE PROPERTIES

| SAMPLE | TENSILE STRENGTH IN KSI | YIELD STRENGTH IN KSI | ELONGATION GL = 4.51 A, IN PERCENT | REDUCTION OF AREA IN PERCENT |
|---------|-------------------------------|-----------------------------|--|---------------------------------|
| Steel A | 94.5, 95.5 | 70.0, 69.5 | 26, 27 | 76, 75 |
| Steel B | 96.5, 97.0 | 83.0, 84.0 | 24, 24 | 73, 71 |
| Steel C | 114, 114 | 106, 106 | 21, 21 | 72, 71 |
| Steel D | 128, 131 | 121, 123 | 20, 20 | 68, 66 |

TABLE B3
BASE METAL CHARPY V-NOTCH PROPERTIES
ABSORBED ENERGY, IN FOOT-POUNDS

| SAMPLE | TEST TEMPERATURE IN DEGREES FAHRENHEIT | LONGITUDINAL ORIENTATION | | | TRANSVERSE ORIENTATION | | |
|---------|---|--------------------------|----------------------------------|------------------------------|------------------------|----------------------------------|------------------------------|
| | | SURFACE LOCATION | QUARTER THICKNESS LOCATION | MID THICKNESS LOCATION | SURFACE LOCATION | QUARTER THICKNESS LOCATION | MID THICKNESS LOCATION |
| Steel A | -40 | PB*,238,218 | PB*,PB*,PB* | PB*,PB*,PB* | 186,166,192 | 259,233,237 | 187,173,189 |
| | -90 | 178,247,PB* | PB*,PB*,PB* | PB*,165,180 | 180,214,238 | 198,PB*,PB* | 163,PB*,PB* |
| | -120 | 168,197,209 | 149,176,PB* | 235,38,142 | 29,33,69,221.5 | 144,PB*,203 | 133,PB*,PD* |
| | -140 | 189,170,210 | 183,187,190 | PB*,61.5,18,19 | 104,187,192 | 151,13,19 | 123,17,190 |
| | -160 | 14.5,17,9.0 | 51.0,9.0,240 | 11.0,13.0,9.0 | 15.5,114,138 | 23.0,14,13 | 18.0,9.5,205 |
| Steel B | -40 | 152,183,196,166 | 197,192,196,193 | 209,184,204,177 | 124,141,132,127 | 102,113,110,126 | 120,131,125,147 |
| | -50 | 152,186,146 | 147,130,155 | 197,190,189 | 113,112,104 | 113,128,119 | 128,111,112 |
| | -60 | 194,188,131 | 120,143,143 | 124,143,143 | 121,110,132 | 94,113,116 | 120,109,112 |
| | -90 | 121.5,114,129 | 107,135,125 | 107,141,127 | 95,100,105 | 106,82,105 | 107.5,99,69 |
| | -120 | 48,110,20,20 | 30,20,27,126 | 117,109,12,75 | 71,71,58 | 68.5,81,72 | 80,66,65 |
| | -140 | 32,60,59 | 7,39,44 | 34,52,103 | 73,42,65 | 69,65,48 | 16,59,80 |
| | -160 | 9.5,15,12 | 26.5,12,10.5 | 8.5,29,21 | 19,13,31 | 60.5,68,17 | 21.5,30,12.5 |
| Steel C | 68 | 185,178,174 | 191,188,188 | 182,189,185 | 136,177,178 | 159,181,178 | 163,183,180 |
| | 0 | 173,178,174 | 180,188,188 | 176,189,185 | 116,150,122 | 153,165,151 | 153,154,154 |
| | -40 | 156,150,149 | 176,166,181 | 183,172,189 | 105,103,108,111 | 148,155,144 | 132,151,136 |
| | -90 | 127,149,165,134 | 185,140,152 | 142,130,135 | 91.5,75,77 | 123,101,107 | 137,111,108 |
| | -120 | 93.5,94,102 | 117,125,106 | 99,123,101 | 56,18,66 | 58.5,69,61 | 67,62,97 |
| | -180 | 14.5,13.5,11.0 | 13.5,52,11.0 | 46.5,57,78 | 6.5,34,20 | 47.0,23,18.5 | 39.5,30,56 |
| | -240 | 9.5,13.5,12.5 | 9.0,46,31 | 18.0,11.5,13.5 | 4.0,9.0,7.5 | 6.0,9.0,9.5 | 4.5,8.5,21 |
| Steel D | 68 | 145,135,147 | 141,147,141 | 142,142,167 | 83.5,92,91 | 114,110,116 | 117,114,123 |
| | 0 | 120 | 135 | 138 | 56 | 100 | 108 |
| | -20 | 114,133,120 | 139,151,140 | 139,151,143 | 42,85,70 | 90,104,104 | 95.5,90,111 |
| | -40 | 100,101,132 | 150,135,145 | 147,142,147 | 55,64,64 | 70,99,112 | 98,99,113 |
| | -50 | 83,116,115 | 118,151,147 | 103,151,143 | 39.5,52,56 | 76,88,89 | 80.5,94,86 |
| | -90 | 96.5,87,78.5 | 112,81,91 | 130,95,106 | 44.5,43,40 | 72.5,50,56 | 72.5,66,17 |
| | -120 | 68,8,57 | 75,76,71 | 76.5,84,66 | 8.0,29,28 | 49,54,55 | 61,53,42 |
| | -180 | 27,10,10 | 46.5,7,21 | 43,12,25 | 6.5,12,18.5 | 33,27,26 | 33.5,36,26 |
| | -240 | 3 | 7 | 10.5 | 6 | 9 | 12.5,16.5 |

PB = Partial break

Note: *Maximum test machine capacity 264 ft-lbs.
Data for information only: not valid according to ASTM E23.

TABLE B4
BASE METAL CHARPY V-NOTCH PROPERTIES
LATERAL EXPANSION, IN MILS

| SAMPLE | TEST TEMPERATURE IN DEGREES FAHRENHEIT | LONGITUDINAL ORIENTATION | | | TRANSVERSE ORIENTATION | | |
|---------|---|--------------------------|----------------------------------|------------------------------|------------------------|----------------------------------|------------------------------|
| | | SURFACE LOCATION | QUARTER THICKNESS LOCATION | MID THICKNESS LOCATION | SURFACE LOCATION | QUARTER THICKNESS LOCATION | MID THICKNESS LOCATION |
| Steel A | -40 | PB,95,90 | PB,PB,PB | PB,PB,PB | 91,89,100 | 81,94,95 | 93,98,96 |
| | -90 | 97,95,PB | PB,PB,PB | PB,96,99 | 96,96,99 | 89,PB,PB | 96,PB,PB |
| | -120 | 86,106,101 | 86,99,PB | 89,32,82 | 22,26,52,106 | 82,PB,98 | 79,PB,PB |
| | -140 | 93,108,100 | 85,97,96 | PB,49,14,13 | 62,94,101 | 89,10,18 | 71,16,103 |
| | -160 | 13,16,11 | 41,10,98 | 6,17,9 | 9,84,PB | 14,11,11 | 11,9,99 |
| Steel B | -40 | 85,87,96,95 | 89,95,96,94 | 80,90,95,95 | 74,82,94,82 | 68,80,74,81 | 78,81,82,89 |
| | -50 | 88,96,95 | 86,90,99 | 90,95,95 | 73,76,75 | 80,81,83 | 88,76,76 |
| | -60 | 94,96,92 | 79,44,98 | 88,92,95 | 82,77,88 | 64,75,85 | 83,69,76 |
| | -90 | 82,80,91 | 76,91,90 | 75,93,90 | 73,67,69 | 73,61,77 | 77,72,50 |
| | -120 | 30,13,13 | 18,26,22,96 | 80,81,16,56 | 48,50,42 | 45,61,52 | 59,46,46 |
| | -140 | 12,50,42 | 7,29,32 | 26,40,72 | 52,27,44 | 42,51,36 | 10,40,60 |
| | -160 | 2,8,10 | 15,10,8 | 3,20,14 | 10,11,16 | 39,30,9 | 15,23,7 |
| Steel C | 68 | 81,92,91 | 87,97,96 | 92,100,101 | 79,90,88 | 87,94,83 | 88,93,93 |
| | 0 | 87,92,91 | 89,97,96 | 89,100,101 | 81,91,81 | 87,94,83 | 84,97,95 |
| | -40 | 91,90,85 | 89,91,92 | 93,86,98 | 71,57,68,73 | 85,86,86 | 75,86,86 |
| | -90 | 82,88,77,76 | 92,83,84 | 80,83,83 | 56,50,48 | 74,65,65 | 79,70,63 |
| | -120 | 60,57,67 | 71,66,67 | 61,70,60 | 34,6,39 | 34,44,42 | 40,35,60 |
| | -180 | 8,9,7 | 8,34,6 | 24,36,48 | 0,22,11 | 29,11,06 | 23,20,36 |
| | -240 | 0,6,4 | 0,29,20 | 6,4,10 | 0,4,0 | 0,3,4 | 0,2,10 |
| Steel D | 68 | 84,76,82 | 81,88,82 | 79,74,88 | 56,61,63 | 73,74,71 | 71,74,80 |
| | 0 | 70 | 77 | 80 | 35 | 62 | 65 |
| | -20 | 68,68,72 | 80,86,82 | 60,82,81 | 27,54,45 | 57,52,64 | 70,60,65 |
| | -40 | 62,63,76 | 90,81,96 | 81,85,85 | 31,34,38 | 47,50,68 | 60,56,70 |
| | -50 | 50,71,72 | 80,84,88 | 64,94,85 | 28,33,36 | 46,57,62 | 52,56,58 |
| | -90 | 55,57,57 | 66,56,60 | 77,58,70 | 27,30,26 | 41,32,36 | 41,40,18 |
| | -120 | 42,9,36 | 43,47,44 | 44,55,41 | 0,19,18 | 25,32,34 | 32,32,26 |
| | -180 | 15,3,4 | 27,2,7 | 23,6,11 | 0,8,14 | 17,19,14 | 14,25,18 |
| | -240 | 2 | 0 | 2 | 0 | 0 | 0, 4 |

PB = Partial break.

TABLE B5
BASE METAL CHARPY V-NOTCH PROPERTIES
FRACTURE APPEARANCE, IN PERCENT SHEAR

| SAMPLE | TEST TEMPERATURE IN DEGREES FAHRENHEIT | LONGITUDINAL ORIENTATION | | | TRANSVERSE ORIENTATION | | |
|---------|---|--------------------------|----------------------------------|------------------------------|------------------------|----------------------------------|------------------------------|
| | | SURFACE LOCATION | QUARTER THICKNESS LOCATION | MID THICKNESS LOCATION | SURFACE LOCATION | QUARTER THICKNESS LOCATION | MID THICKNESS LOCATION |
| Steel A | -40 | PB,PB,PB | PB,PB,PB | PB,PB,PB | 100,100,100 | 100,100,100 | 100,100,100 |
| | -90 | 100,100,PB | PB,PB,PB | PB,100,100 | 100,100,100 | 100,PB,PB | 100,PB,PB |
| | -120 | 91,90,90 | 100,100,PB | 100,26,100 | 27,30,30,100 | 100,PB,100 | 100,PB,PB |
| | -140 | 90,90,90 | 90,90,90 | PB,14,0,0 | 100,100,100 | 51,0,0 | 100,0,100 |
| | -160 | 0,0,0 | 0,0,100 | 0,6,11 | 0,50,PB | 3,0,0 | 0,0,69 |
| Steel B | -40 | 100,100,100,80 | 100,100,100,100 | 100,100,100,90 | 50,100,69,65 | 77,51,60,65 | 82,66,65,100 |
| | -50 | 100,100,100 | 59,62,80 | 100,100,100 | 72,72,70 | 60,61,56 | 66,65,76 |
| | -60 | 100,100,62 | 62,75,75 | 70,69,64 | 63,62,56 | 59,50,50 | 70,69,70 |
| | -90 | 45,45,45 | 50,51,45 | 50,57,45 | 60,60,60 | 66,40,70 | 56,56,40 |
| | -120 | 18,29,0,0 | 0,0,0,4,2 | 29,29,0,35 | 33,27,30 | 21,27,27 | 35,20,20 |
| | -140 | 0,10,10 | 0,3,10 | 0,10,33 | 39,30,39 | 26,30,26 | 5,26,35 |
| | -160 | 0,0,0 | 0,0,0 | 0,0,0 | 0,0,0 | 3,10,0 | 0,0,0 |
| Steel C | 68 | 100,100,100 | 100,100,100 | 100,100,100 | 100,100,100 | 100,100,100 | 100,100,100 |
| | 0 | 100,100,100 | 100,100,100 | 100,100,100 | 100,100 | 100,100,100 | 100,100,100 |
| | -40 | 100,90,90 | 100,100,100 | 100,100,100 | 100,100,100,100 | 100,100,100 | 100,100,100 |
| | -90 | 75,69,76,70 | 69,80,84 | 90,92,100 | 66,47,55 | 65,79,71 | 61,69,68 |
| | -120 | 36,33,45 | 50,73,54 | 43,68,42 | 27,0,14 | 30,25,30 | 33,39,45 |
| | -180 | 0,0,0 | 0,16,0 | 10,20,23 | 5,5,3 | 14,3,0 | 10,3,14 |
| | -240 | 0,0,0 | 0,0,0 | 0,0,0 | 0,0,0 | 0,0,0 | 0,0,0 |
| Steel D | 68 | 100,100,100 | 100,100,100 | 100,100,100 | 100,100,100 | 100,100,100 | 100,100,100 |
| | 0 | 100 | 100 | 100 | 100 | 100 | 100 |
| | -20 | 77,100,90 | 100,100,100 | 100,100,100 | 44,73,60 | 100,100,100 | 100,100,100 |
| | -40 | 69,77,100 | 100,100,100 | 50,100,100 | 50,50,59 | 90,80,100 | 100,100,100 |
| | -50 | 66,66,69 | 69,100,100 | 67,100,100 | 47,34,39 | 56,65,74 | 66,65,58 |
| | -90 | 54,55,66 | 58,63,51 | 61,55,59 | 35,27,30 | 42,39,52 | 59,62,39 |
| | -120 | 27,5,30 | 30,44,34 | 33,39,39 | 0,0,10 | 34,40,39 | 39,47,30 |
| | -180 | 3,0,0 | 10,0,0 | 6,0,0 | 0,0,0 | 0,5,0 | 0,0,0 |
| | -240 | 0 | 0 | 0 | 0 | 0 | 0 |

PB = Partial break.

TABLE B6
DROP WEIGHT DYNAMIC TEAR TEST DATA

| <u>SAMPLE</u> | <u>TEST TEMPERATURE, IN DEGREES C</u> | <u>ENERGY ABSORBED IN FOOT-POUNDS</u> |
|---------------|---|---|
| STEEL A | -60 | PB |
| | -70 | 112; PB |
| | -80 | 62 |
| | | |
| STEEL B | -20 | PB |
| | -40 | 802 |
| | -60 | 597 |
| | -70 | 382 |
| | -80 | 17 |
| | | |
| STEEL C | -20 | PB |
| | -40 | 1,107; PB |
| | -50 | PB |
| | -60 | 332; 50 |
| | -70 | 117 |
| | -80 | 237 |
| | | |
| STEEL D | 0 | PB |
| | -20 | 557 |
| | -40 | 404 |
| | -60 | 72 |
| | -80 | 42 |
| | | |

PB = Partial break

TABLE B7
THROUGH THICKNESS HARDNESS SURVEY

| | <u>STEEL A</u> <u>in RB*</u> | <u>STEEL B</u> <u>in RB*</u> | <u>STEEL C</u> <u>in RC*</u> | <u>STEEL D</u> <u>in RC*</u> |
|--|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| <u>SURFACE</u> | 95 | 98,98 | 21 | 26 |
| <u>DEPTH BELOW SURFACE,</u> <u>in sixteenths of an inch</u> | | | | |
| 1 | 98 | 98,98,100;RC20 | 22,24 | 27,28 |
| 3 | 95 | 98,98,98;RC18 | 22 | 28 |
| 5 | 95 | 96,99 | 23 | 28 |
| 7 | 95 | 96,98 | 22 | 28 |
| 9 | 96 | 97,100 | 22 | 29 |
| | CL | | | |
| 11 | 94 | 97,99 | 22 | 26 |
| 13 | 95 | 97,98 | 22 | 25 |
| 15 | 94 | 97,98 | 20 | 24 |
| | | CL | CL | CL |
| 17 | 93 | 97,98 | 20 | 24 |
| 19 | 94,96;RC14 | 97,98 | 22 | 26 |
| 21 | - | 97,100 | 22 | 27 |
| 23 | - | 96,96,102 | 21 | 28,28 |
| 25 | - | 97,102 | 22 | 28,28 |
| 27 | - | 98,103 | 22 | 28 |
| 29 | - | 100,105 | 22 | 28 |
| 31 | - | 99,102;RC26,27 | 22 | 28 |
| <u>SURFACE</u> | 96 | 98,98;BHN229 | 27 | 25 |

*in hardness scale noted unless otherwise indicated

R_B = Rockwell B scale

R_C = Rockwell C scale

BHN = Brinell Hardness number

CL = Plate Centerline

APPENDIX C - WELDING PARAMETERS

TABLE C1
WELDING PARAMETERS FOR CTS TEST

| | |
|-----------------|---------------------------------|
| Process | Shielded Metal Arc Welding |
| Filler | AWS A5.5, E11018M |
| Filler Diameter | 5/32" |
| Position | Flat (1F) |
| Joint | Fillet |
| Preheat | None ((RT) |
| Polarity | Direct Current Reverse Polarity |
| Current | 110-120 Amps |
| Voltage | 22-23 Volts |
| Technique | Stringer |
| Bead Sequence | Single Pass |
| Travel | 5-7 inches/minute |
| Heat Input | 21-33 KJ/inch |

TABLE C2
WELDING PARAMETERS FOR SMALL SCALE TEST WELDMENT

| | <u>STEEL A</u> | <u>STEEL C</u> |
|------------------------|-----------------------|-----------------------|
| Process | SMAW | SMAW |
| Filler Metal | AWS A5.5, E9018M | AWS A5.5, E11018M |
| Root Passes Diameter | 1/8" | 1/8" |
| Fill Passes Diameter | 5/32" | 5/32" |
| Position | Flat (1G) | Flat (1G) |
| Joint, as per AWS D1.1 | B-U5a* | B-U5a* |
| Preheat | None (RT) | None (RT) |
| Interpass | 200F | 200F |
| Polarity | DCRP | DCRP |
| Current | | |
| Root Passes | 120-130 amps | 120-130 amps |
| Fill Passes | 150-160 amps | 150-160 amps |
| Voltage | 19-22 volts | 19-22 volts |
| Technique | Stringer Only | Stringer Only |
| Bead Sequence | Multipass/Split Layer | Multipass/Split Layer |
| Travel Speed | 5-6 in/minute | 5-6 in/minute |
| Heat Input | | |
| Root Passes | 23-34 KJ/in. | 23-34 KJ/in. |
| Fill Passes | 28-42 KJ/in. | 28-42 KJ/in. |
| Back Gouge | Yes | Yes |

*Double Bevel Groove Butt Joint; square side of "K" used
for fusion line and HAZ study

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